Mirror fermions and the hierarchy problem

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Abstract

The introduction of strongly-interacting mirror fermions with masses between the weak scale and 1 TeV could offer a viable alternative to the Higgs mechanism. The framework provided solves the hierarchy problem naturally and predicts a rich phenomenology for present and future experiments.

Even though present electroweak precision measurements are more or less consistent with the standard-model, the source of the masses of the known fermions and the weak vector bosons, as well as the unitarizing sector of the theory, remain unknown. A fundamental scalar field acquiring a non-zero vacuum expectation value could provide a solution. However, not only such a field has not been observed yet, but it is also hard to understand why its mass is so much smaller than the Planck scale.

Efforts to introduce new strongly-interacting fermions as an alternative to the Higgs mechanism, in the context of technicolor theories for instance, are difficult to reconcile with precision measurements and unification schemes. This recently led [1] to the introduction of new heavy fermions with mirror weak-charge assignments, which can overcome these problems easier. Previous efforts to introduce mirror fermions can be found in a review [2]; such extensions have also been proposed as a solution to the strong CP problem [3]. Our interest will be focused here on a particular version of these fermions which we name "katoptrons". These are differentiated from usual mirror fermions by the fact that they interact according to an additional gauge symmetry whose coupling becomes strong at around 1 TeV, and which gives to all of them dynamical masses of that order of magnitude.

In particular, we consider the gauge structure $SU(4)_{PS} \times SU(2)_L \times SU(2)_R \times SU(3)_{2G}$, under which the standard-model fermions transform like three copies of $(\mathbf{4}, \mathbf{2}, \mathbf{1}, \mathbf{1})$ and $(\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2}, \mathbf{1})$ and the katoptrons like $(\mathbf{4}, \mathbf{1}, \mathbf{2}, \mathbf{3})$ and $(\bar{\mathbf{4}}, \mathbf{2}, \mathbf{1}, \mathbf{3})$. At the Pati-Salam scale Λ_{PS}, the gauge symmetry is reduced according to $SU(4)_{PS} \times SU(2)_R \longrightarrow SU(3)_C \times U(1)_Y$. As is clearly shown in Fig. 1, this easily leads to a unification of all gauge couplings, including the $SU(3)_{2G}$ coupling, at a scale Λ_{GUT} consistent with proton life-time bounds [4]. Moreover, the $SU(3)_{2G}$ coupling becomes naturally strong at a scale $\Lambda_M \approx 1$ TeV. It allows the formation of katoptron condensates at that scale, which break the electroweak symmetry dynamically. This provides us with the first dynamical-symmetry-breaking scenario that postdicts correctly the weak scale with natural assumptions (compare with Ref. [5] for instance), and thus constitutes a reasonable solution to the hierarchy problem.

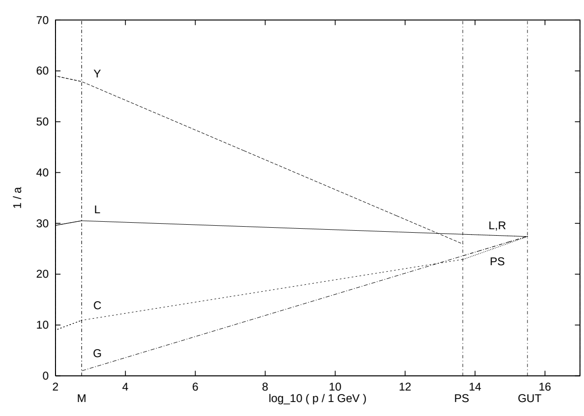

Figure 1. The running of the inverse fine-structure constants $\alpha^{-1}_{Y,L,C,G}$ and later $\alpha^{-1}_{R,PS}$, corresponding to the gauge-symmetry breaking channel $SU(4)_{PS} \times SU(2)_R \longrightarrow SU(3)_C \times U(1)_Y$. The vertical lines, starting from small energies, correspond to the scales $\Lambda_M = 10^{2.75}$ GeV, $\Lambda_{PS} = 10^{13.65}$ GeV and $\Lambda_{GUT} = 10^{15.5}$ GeV.

The need to generate masses for the ordinary fermions leads us to consider scenarios in which the group $SU(3)_{2G}$ breaks after it becomes strong. Standard-model fermions can then mix with their mirror partners via gauge-invariant terms in the mass matrix. This can happen in a way that reproduces correctly not only the mass hierarchies but also the mixings of the charged fermions and neutrinos with each other [1],[4]. The mechanism responsible for the breaking of $SU(3)_{2G}$ remains however an important open problem.

This breaking is expected to reduce the contribution of the katoptrons to the S parameter by roughly a factor of 2 [6]. This fact, together with the existence of light Majorana mirror neutrinos and negative vertex corrections allow the S parameter to be in agreement with experimental constraints [1],[4]. Vertex corrections are sufficiently large if the right-handed top-quark anomalous weak coupling δg_R^t is at least as large as δg_R^b. The latter is extracted from the deviation of the bottom-quark asymmetry A_b from its standard-model prediction, which being a 2.5 σ effect could be the first experimental indication at hand for the existence of katoptrons [1]. Moreover, problems with the $\Delta\rho$ parameter can be circumvented since the top-bottom quark mass hierarchy can be reproduced by gauge-invariant terms in the mass matrix.

If one regards the A_b anomaly as a first indication for the existence of a heavy mirror sector, one should investigate what signals should be expected next in the planned colliders. At the NLC and the Tevatron III, the katoptron model forces V_{tb} to deviate from its standard-model value, predicting a value around 0.95 [1]. The measurement of an anomalous top-quark coupling δg_R^t, which could potentially be even larger than δg_R^b, would also support the katoptron scenario. The LHC could produce mirror fermions and their associated scalar resonances directly, giving however signals that would hardly be distinguished from corresponding fourth-generation or technicolor signals respectively [6]. Note that, since the strong group $SU(3)_{2G}$ is eventually broken, it is likely that no vector resonances are formed and that no WW hard scattering can be observed.

The ultimate proof for the existence of katoptrons would come from a lepton collider with c.o.m. energies on the order of 4 TeV or higher, like the muon collider [6]. Such a collider would be able to probe the weak charges of the new fermions directly and thus check their mirror-charge assignments. The forward-backward asymmetry of the katoptrons as a function of collider energy is shown in Fig. 2.

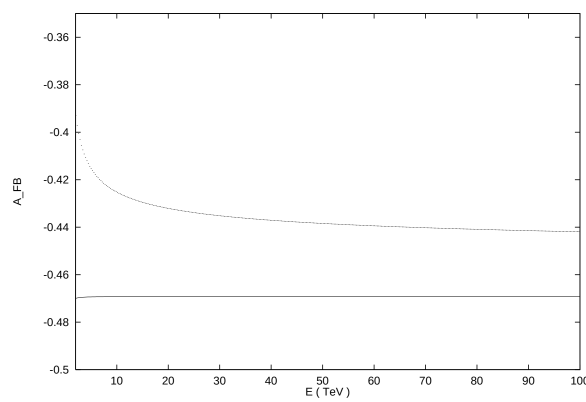

Figure 2. The forward-backward asymmetry A_{FB} as a function of lepton-collider c.o.m. energy. The dotted line corresponds to A_{FB} after $SU(3)_{2G}$ corrections have been taken into account.

It becomes evident from this figure how the strong $SU(3)_{2G}$ coupling smears out the directional information of the out-going katoptrons at low energies, underlining therefore the need for very powerful lepton colliders.

To conclude with a unifying perspective, it is useful to remember that some representations of gauge groups that arise in superstring theories include the standard-model fermions not only with their supersymmetric, but also with their mirror partners. Contrary to what is usually done nowadays, the present program is based on avoiding light scalar fields by keeping the supersymmetric partners decoupled at unification scales and bringing the mirror partners close to the weak scale, whose magnitude is, as shown above, an output of the model.

References

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